Indian J. Phys. **70B** (6), 495–504 (1996)

IJP B
— an international journal

Evidence for quasi 4-level operation of erbium doped fiber lasers on various laser transitions through studies of laser relaxation oscillations under pump modulation

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Received 23 July 1996, accepted 16 September 1996

Abstract : This paper shows through a study of relaxation oscillation frequencies that erbium doped fiber lasers using erbium doped in Al/P matrix show quasi 4-level behaviour at the shorter wavelength of 1534 nm The study also reconfirms the quasi 4-level behaviour of the laser at the longer wavelength of 1559 nm obtained from spectroscopic investigations. In addition, the resonator losses have been determined for various resonator geometries at different oscillation wavelengths

Keywords : Fiber lasers and amplifiers, relaxation oscillations, quasi 4-level systems

PACS Nos. : 42.55.Wd, 42.60 Da, 42 81 Cn

1. Introduction

The high gain and long interaction lengths possible in erbium doped singlemode fibers make them ideally suitable for the construction of efficient fiber amplifiers and lasers. Even though the EDFL (erbium doped fiber laser) is essentially a 3-level laser system, it shows a quasi 4-level behaviour in the longer wavelength region around 1.56 μm [1] because of the stark splitting of the relevant energy levels. The actual number of stark levels of the erbium ion depends on the host matrix into which it is doped. From fluorescence studies, Desurvire and Simpson [2] have observed a splitting of the ground state of the erbium ion into 5-levels and the metastable state of the erbium ion into 4-levels in aluminosilicate matrices.

It is possible to obtain evidence on whether the laser is indeed working as a 3-level or 4-level system, by modulating the pump and studying the relaxation oscillation frequencies 'ω' of the laser output. This simple and convenient technique can be used as a preliminary test to determine if the laser is working as a 3-level or 4-level system, the results of which can be further confirmed, if needed, through detailed low temperature, high resolution spectroscopic studies of the fluorescence. This paper presents a study of pump modulation based relaxation oscillations of the erbium doped fiber laser's output, at the shorter wavelength region around 1534 nm and also at the longer wavelength of 1559 nm for three different resonator configurations. It provides for the first time, as far as we are aware, a confirmation that the 1534 nm laser transition also behaves like a quasi 4-level laser system in an EDFL.

2. Theory

For a 4-level system, the relaxation oscillation frequency ω and the input pump power P are related through the expression given below [3,4] :

$$\omega^2 = \left(\frac{P}{P_{th}} - 1\right)\left(\frac{\mu}{\tau_2 \tau_c}\right), \tag{1}$$

where τ_2, τ_c, P_{th} and μ are the fluorescence lifetime, cavity lifetime, threshold pump power and the overlap integral of the pump and laser fields in the fiber respectively The X-intercept of the graph with ω^2 on the Y-axis and P on the X-axis will give the threshold pump power and the Y intercept will give $\mu/\tau_2\tau_c$.

Knowing the fluorescence lifetime, the cavity lifetime can be estimated and therefore we can also estimate the resonator losses, since

$$\tau_c = \frac{2nd}{c}\left(\left[1/\ln\left\{1/(1-x)\right\}\right]\right) \tag{2}$$

where n is the effective refractive index, d the length of the resonator cavity, c the velocity of light and x the fractional loss per pass through the resonator.

Derivation of the expression for the 3-level system following the same method detailed in [3,4], yields the following equation for the relaxation oscillation frequencies

$$\omega^2 = \left(\frac{P}{P_{th}} - 1 + K\right)\left(\mu/\tau_2\tau_c\right) + \left(1/\tau_c^2\right), \tag{3}$$

where K is the inverse of the number of longitudnal modes supported by the cavity.

When compared to eq. (1), eq. (3) has two additional terms on the R.H.S. The term that depends on K can be ignored since K will be very small. For example, for a fiber length of 1.5 m, the number of modes coupled into the fluorescence linewidth is approximately 10^7 and hence K is of the order of 10^{-7}. Further, when $P = 0$, $\omega^2 \approx (1/\tau_c^2)(1-\mu\tau_c/\tau_2)$ which to a first approximation can be replaced by $(1/\tau_c^2)$. It can also be seen that when $P = P_{th}$, $\omega^2 = (1/\tau_c^2)$.

3. Experimental

The erbium doped fiber used for constructing EDF lasers had 1200 ppm-wt of erbium doped in an Al/P silica matrix, a N.A of 0.13 and core/cladding diameter of 6.8/80 μms. The resonator configurations studied were (i) a linear resonator with microscope objectives as intracavity elements (Res I) (Figure 1), (ii) a linear resonator with dichroic mirrors butted to the fibers (Res II) and (iii) the ring resonator (Res III) (Figure 2). The pump wavelength

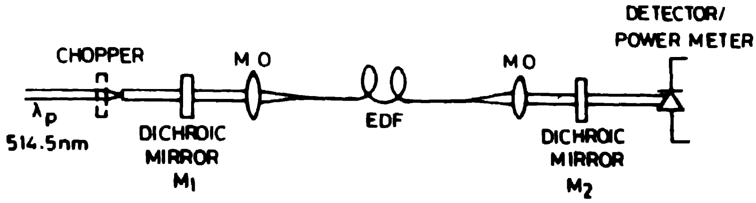

Figure 1. Linear resonator configuration (Resonator I) for the erbium doped fiber laser

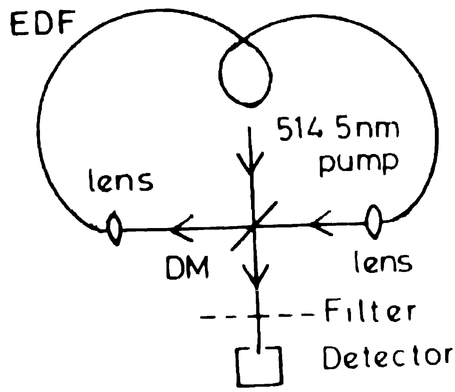

Figure 2. Ring resonator configuration (Resonator III) for the erbium doped fiber laser

used for the study was the 514.5 nm line from an argon ion laser. Plane dichroic mirrors with 20% and 60% reflectivities at the pump and laser wavelengths respectively were used to construct the linear resonators (Figure 1). The ring laser was constructed with a single dichroic mirror which had 80% and 3% reflectivities at the pump and signal wavelengths respectively, when inclined at 45° to the pump beam (Figure 2). For all the configurations, the variation of the CW laser output power and the CW laser linewidth, with input pump power, was studied and some typical results are given in Figures 3 and 4.

The pump beam was mechanically chopped and the laser output pulses were detected using a reverse biased InGaAs photodiode and monitored on a 250 MHz Iwatsu oscilloscope. The relaxation frequencies at various laser transitions were monitored as a function of input pump power and this variation is depicted in Figure 5 for the different resonator configurations studied and for different fiber lengths. From this study, the threshold pump powers and resonator losses were estimated for various transitions using

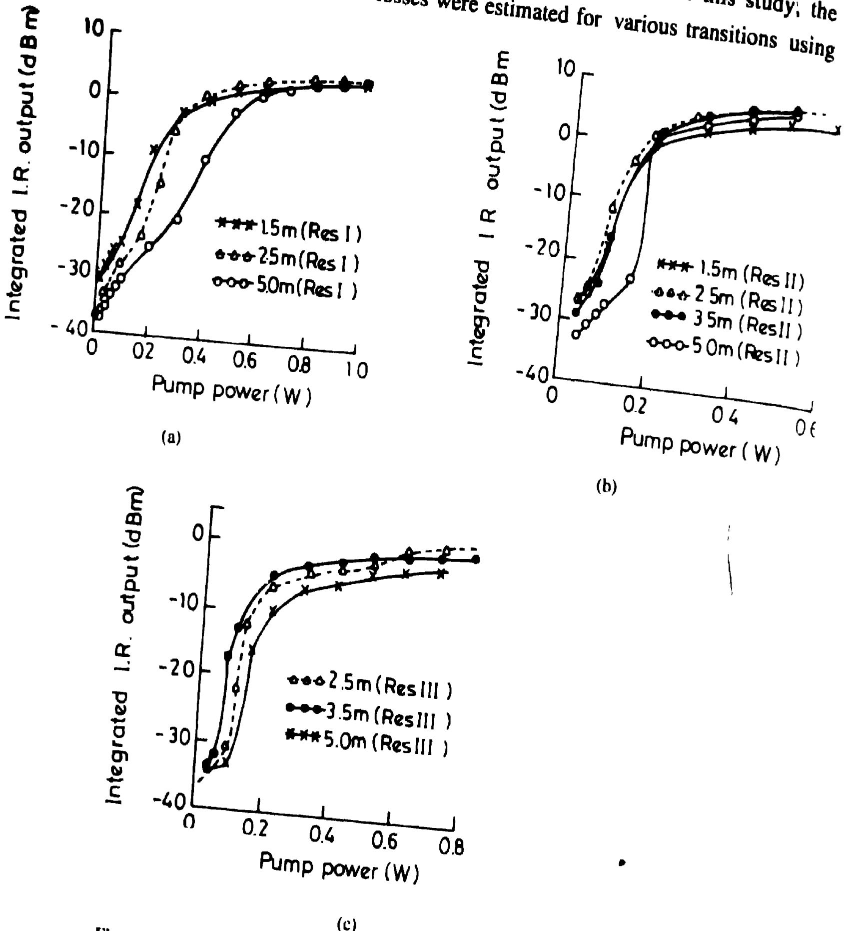

Figure 3. Variation of the laser output power with input pump power for different fiber lengths for (a) Resonator I, (b) Resonator II and (c) Resonator III.

eq. (1) and eq. (2) for 4-level and eq. (3) and eq. (2) for the 3-level laser systems respectively.

4. Discussion

The threshold powers estimated from studies of the laser relaxation oscillation frequencies at $\lambda = 1534$ nm, using the 3-level and 4-level models and those measured from the variation of laser's CW output characteristics with pump power, are displayed in Table 1. It can be seen from the table that the threshold pump powers obtained from these two studies agree closely if the EDFL is considered to be a 4-level system. Further, if we consider the 3-level model, the single pass fractional loss (x) is too low for the reflectivities of the mirrors used in the experimental study and the threshold pump powers obtained are nearly twice the

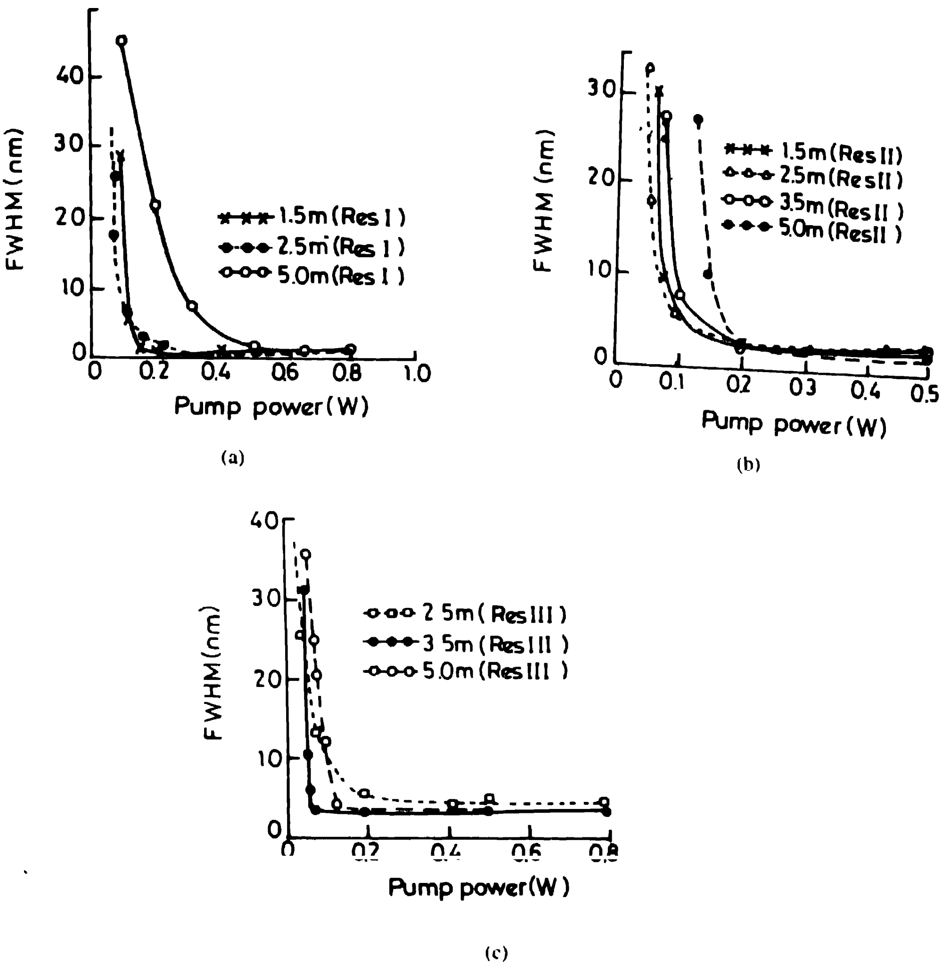

Figure 4. Variation of linewidth of the laser output with input pump power for different fiber lengths for (a) Resonator I, (b) Resonator II and (c) Resonator III.

value obtained from the CW studies. Thus, this study reveals that the EDFL's investigated by us behave like quasi 4-level system even at the shorter wavelength of 1534 nm.

Table 2 displays similar information for the EDFL's working at about 1559 nm. Again reasonably close agreement is obtained between the results obtained from the relaxation oscillation studies using the 4-level model and that obtained from CW characteristics of this laser. These results obtained from pump modulation studies are also in conformity with the previously reported observation of quasi 4-level operation of EDFL's at the longer wavelength of 1.56 μm [1].

Thus, this study of the relaxation oscillation frequency reveals that the EDFL's investigated by us, do indeed behave like quasi 4-level systems at the shorter wavelength of

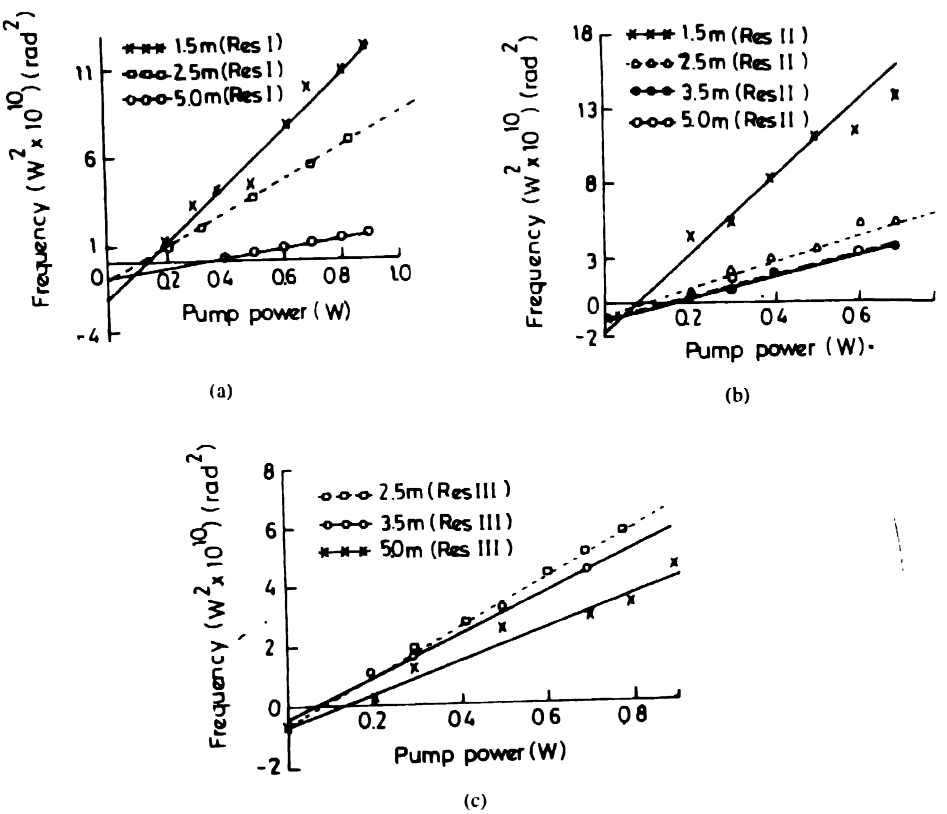

Figure 5. ω^2 *versus* pump power for different fiber lengths for (a) Resonator I, (b) Resonator II and (c) Resonator III

Table 1. Threshold pump powers and resonator losses obtained from CW and dynamic studies of the erbium doped fiber lasers working in the shorter 1534 nm wavelength band

Wavelength (nm)	CW studies P_{th} (W)	Dynamic studies P_{th} (W)		Fractional resonator loss (x)		Remarks
		4 level	3 level	4 level	3 level	
1533	0 13	0 13	0 28	0 98	0.002	Res I, Fiber length = 1 5 m
1533	0 07	0 07	0 14	0.94	0.007	Res II, Fiber length = 1 5 m
1533 8	0 08	0.07	0 22	0.75	0.002	Res I, Fiber length = 2 5 m
1534 2	0 32	0.30	0.58	0.97	0.004	Res I, Fiber length = 5.0 m

Table 2. Threshold pump powers and resonator losses obtained from CW and dynamic studies of the erbium doped fiber lasers working in the longer 1550-1560 nm wavelength band.

Wavelength (nm)	CW studies P_{th} (W)	Dynamic studies P_{th} (W) 4 level	Dynamic studies P_{th} (W) 3 level	Fractional resonator loss (x) 4 level	Fractional resonator loss (x) 3 level	Remarks
1554 8	0 09	0 117	0 24	0.97	0 003	Res II, Fiber length = 3.5 m
1556	0.08	0.080	0 20	0 93	0.003	Res II, Fiber length = 2.5 m
1558.2	0.13	0.130	0.26	0 97	0.004	Res III, Fiber length = 5.0 m
1559.0	0.15	0.14	0 25	0 98	0 003	Res II, Fiber length = 5.0 m
1559.6	0 125	0 130	0.255	0 99	0 003	Res III, Fiber length = 2.5 m
1559.8	0.08	0 075	0 16	0.76	0.002	Res III, Fiber length = 3.5 m

1534 nm. However, we could not perform low temperature fluorescence and absorption studies for confirmation of the same, since we do not have adequate facilities for such high sensitivity, high resolution spectroscopic studies. A scrutiny of the stark levels of erbium ion in aluminosilicate matrices observed by Desurvire *et al* [2] (see Figure 6) shows that the

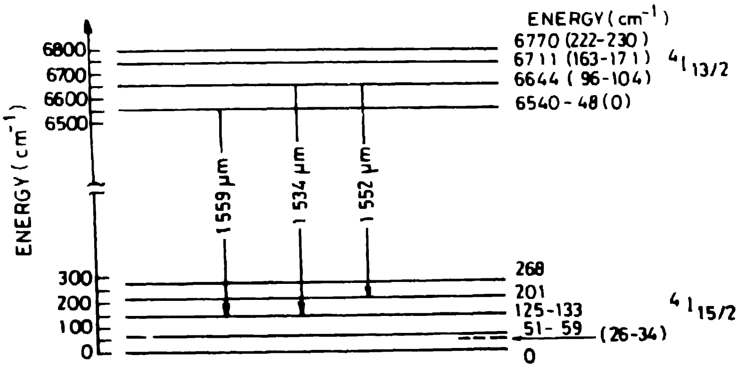

Figure 6. Energy level diagram showing the stark components of the $^4I_{15/2}$ and $^4I_{13/2}$ states of the erbium ion in aluminosilicate matrices [Ref. 2]

longer wavelength transition at 1559 nm terminates on a J level 125–133 cm^{-1} above the ground state and this transition could therefore exhibit quasi 4-level behaviour. The laser transitions observed by us can probably be assigned within experimental errors to the three different transitions designated as the 1534 nm, 1552 nm and 1559 nm transition by

Desurvire and Simpson [2] (refer to Figure 6). It can be seen from Figure 6 that the 1534 nm and 1552 nm transitions terminate on J levels 125–133 cm^{-1} and 201 cm^{-1} respectively, above the ground state and these transition assignments of [2] are compatible with this present evidence for quasi 4-level behaviour obtained from this study.

The fractional resonator loss 'x' per pass through the resonator, obtained from the study on relaxation oscillation frequencies, includes reabsorption losses at the laser wavelengths, the losses due to the mirror reflectivities at 1.5 μm and the losses incurred at this wavelength while it is coupled back into the fiber *via* the microscope objectives. The variation in the resonator losses that is obtained experimentally with the different resonator configurations and fiber lengths are due to the variation in the fraction of the signal power that is fedback into the resonator due to changes in the signal recoupling losses and mirror reflectivities. Signal recoupling efficiency was generally low for the Resonator I configuration. This loss, combined with the losses due to mirror reflectivities (60% reflectivity only at the signal wavelengths), resulted in high fractional losses. On the other hand, for the Resonator II configuration, the fraction of signal fedback into the resonator was higher because of butt coupling which lowers fresnel losses. The fraction of the signal power fedback into the resonator was high, even for the Resonator III configuration, as output coupling at the laser wavelengths was lower (3% only) in this configuration. But, reabsorption losses were higher for both Resonator II and Resonator III configurations, as pump coupling was lower due to experimental constraints. Thus, the fractional losses remained high in spite of higher signal feedback in these resonators II and III. A scrutiny of the results tabulated in Tables 1 and 2 shows that lowest fractional losses for Resonator I configuration was obtained for a fiber length of 2.5 m for the 1534 nm wavelength. In Resonator II configuration, lowest fractional loss was obtained at 1556 nm for a fiber length of 2.5 m. Further, in Resonator III configuration, the lowest loss was obtained at 1559 nm for the fiber length of 3.5 m. This behaviour is apparently due to the relatively better feedback and lower reabsorption losses that were experimentally realised for these fiber lengths in their respective resonator configurations.

The variation of the laser wavelengths with fiber length and resonator configuration is governed by the effect of reabsorption losses on the gain spectrum from the fiber (for a single pass through the fiber), and the signal losses, due to other factors like losses incurred while coupling the signal back into the fiber, mirror reflectivities *etc*. In EDF's, absorption losses are higher at the fluorescence peak near 1534 nm and lower at longer wavelengths of the fluorescence band. When the pump power coupled into the fiber is low, the fiber will not be uniformly or fully excited along its whole length. Therefore, at these low pump powers, population inversion will decrease along the fiber length from the launch point of the pump, leading to higher reabsorption losses for long fiber lengths. Under such conditions of low population inversion, the output spectrum from the fiber will shift predominantly to the longer wavelengths near 1559 nm where absorption losses are lower.

This is apparently the case for resonator II and III, where the lasing wavelengths are at the longer wavelengths near 1559 nm, even when signal losses due to other factors are low. When the pump power coupled into the fiber increases, the fiber becomes fully excited, leading to lower reabsorption effects. The output spectrum from the fiber in this case will be near the fluorescence peak at 1534 nm and the gain at this wavelength grows relatively faster than that at 1559 nm. Therefore, if the pump power coupled in becomes sufficient to fully excite the fiber length, the lasing wavelength will shift to the shorter wavelength at 1534 nm. This was experimentally observed by us for the shorter fiber lengths of 1.5 m and 2.5 m in the ring resonator (Res III) configuration. For the 1.5 m long EDF in the ring resonator configuration, the lasing wavelengths shifted from 1559 nm at the low pump power of 0.08 W to 1534 nm for pump powers higher than 0.2 W. Similarly, for the 2.5 m long EDF in this configuration, the lasing wavelength shifted from 1559 nm at 0.15 W to the shorter 1534 nm for pump powers higher than 0.6 W.

In the Resonator I configuration, pump coupling was relatively higher, leading to lower reabsorption losses in the fiber. This in turn resulted in a gain spectrum that peaked at 1534 nm. Since signal losses due to coupling and mirror reflectivities were higher in this configuration, these losses could be compensated only at 1534 nm, where gain was high enough. Therefore, all the fiber lengths lased only at the fluorescence peak at 1534 nm and the threshold pump powers required was also high.

If the variation of the relaxation oscillation frequency 'ω' with pump power is studied without any frequency selective device before the detector, change in lasing wavelengths with pump power results in a change in slope of the variation of ω^2 with pump power P. The study of resonator losses and the lasing wavelengths shows that for EDF's in the ring resonator configuration, which has the lowest signal output coupling, signal losses are low enough to provide tunability in the lasing wavelengths by varying the pump power. The threshold pump powers required for the onset of oscillations at the shorter wavelength of 1534 nm when compared to that at the longer wavelength of 1559 nm scaled roughly as the ratio of the absorption cross section at the 1534 nm wavelength to that at 1559 nm wavelength.

5. Conclusions

A study of relaxation oscillations of an EDFL using erbium doped Al/P silica fiber, shows a quasi 4-level behaviour for the shorter wavelength laser transition of 1534 nm and this has been apparently obtained for the first time through this study. Similar evidence obtained by us for 1559 nm additionally reconfirms that this EDFL exhibits quasi 4-level behaviour for the longer wavelength of 1559 nm. Further, this simple technique also provides an estimation of the resonator losses in the laser. Out of the three resonator configurations studied by us, the ring resonator configuration gave a larger tuning range, since signal feedback losses were minimum for this resonator configuration.

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